I_Q: What it is, what it isn't, and how to use it

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Introduction

A device's quiescent current, or I_Q, is an important yet often misused parameter for low-power, energy-efficient designs. In many battery-powered applications, such as metering, wearables, building security and the Internet of Things (IoT), the current drawn from the battery in a standby condition with light or no load defines the total run time of the system. In integrated switch converters, the I_Q is only one portion of this battery current. This article defines I_Q and how it is measured, explains what I_Q is not and how it should not be used, and gives design considerations on how to use I_Q while avoiding common measurement errors. This article applies to any of the Texas Instruments (TI) TPS61xxx, TPS62xxx, TPS63xxx, or TPS650xx devices.

What I_Q is

Unless otherwise noted in the datasheet for a part, I_Q is defined as the current drawn by the IC in a no-load and nonswitching but enabled condition. "No load" means that no current leaves the IC to the output. Typically, this would be current leaving via the SW pin on buck converters or via the V_{OUT} pin on boost converters. All of the I_Q simply travels inside the IC to ground. "Nonswitching" means that no power switch in the IC is on (closed). This includes the main or control switch as well as the synchronous rectifier if both are integrated into the IC. In other words, the IC is in a high-impedance condition with a power stage that is completely disconnected from the output (except for integrated MOSFET body diodes on some devices that cannot be turned off). "Enabled" means that the IC is turned on via its EN pin and is not in a UVLO or other shutdown condition. I_Q measures operating current, not shutdown current, so the device must be on. Lastly, I_Q is meaningful only in power-save mode, so if this mode is an option for the particular device, it must be enabled. If the device runs in pulse-width-modulation (PWM) mode, then the input current to the power stage and switching losses more than dwarfs the miniscule amount of current, the I_Q, required to run the device.

I_Q fundamentally comes from two inputs: V_{IN} and V_{OUT}. The datasheet lists whether the I_Q comes from either or both pins. Figure 1 shows the I_Q specification from the datasheet for the TI TPS61220/21/22,[1] which are boost converters that draw their I_Q from both V_{IN} and V_{OUT}. Typically, a buck converter draws I_Q only from its input, while a boost converter or buck-boost converter draws I_Q from both the input and the output.

I_Q measures the current required to operate the device's basic functionality, which includes powering things like the internal precision reference voltage, an oscillator, a thermal shutdown or UVLO circuit, the device's state machine or other logic gates, etc. I_Q does not include any input current to the power stage or gate drivers, as it is measured in a nonswitching condition where these currents are zero. The reason for measuring I_Q in this condition is that it is solely dependent on the IC, whereas the power-stage input current and gate-drive current are dependent on the selected external components, which in most cases dictate how often the IC switches in its power-save mode. Thus, I_Q is an IC measurement, whereas including the other two currents is a system measurement. TI does not control and cannot guarantee such a system measurement but does control and can specify an IC measurement. In fact, TI guarantees the I_Q specification and, for devices whose datasheets specify a maximum value for the I_Q, tests it on each and every device that is produced. This is done by enabling the device, setting it to the test conditions specified in its datasheet, and then artificially raising (with externally applied voltages) the output voltage, FB pin, and any other pin voltages high enough to cause the IC not to switch. With no load and power-save mode enabled (if available), the input current to the IC becomes the I_Q.

What I_Q isn't

I_Q is not the no-load input current. As previously mentioned, the I_Q is simply the "overhead" current required to operate the IC's basic functionality. It does not include the

Figure 1. I_Q specification from TPS61220/21/22 datasheet

DC/DC STAGE							
PARAMETER			TEST CONDITIONS	MIN	TYP	MAX	UNIT
I_Q	Quiescent current	V_{IN}	I_O = 0 mA, V_{EN} = V_{IN} = 1.2 V, V_{OUT} = 3.3 V		0.5	0.9	µA
		V_{OUT}			5	7.5	µA

input current into the power stage (current that is actually transferred to the output) or current required to operate the gate drivers. Even at no load, the device still switches to keep the output regulated. Some losses always exist at the output, such as loss from the voltage divider used to set the output voltage; leakage current into the load or through the output capacitor; pull-up resistors; etc. Because these losses cause voltage decay at the output capacitor, the IC must switch every so often to replenish the power lost. So, a no-load input-current measurement violates the requirements that the IC must be in a nonswitching condition and that no current may leave the IC to recharge V_{OUT}. As an example, Figure 2 shows no-load operation for the TPS61220 boost converter, with an input voltage of 1.2 V and an output voltage of 3.3 V. The IC switches approximately every 1.75 ms to regulate the output voltage. This period depends on V_{IN}, V_{OUT}, and the external components and affects how much average input current is drawn. During phase #1, the IC is switching—either the high-side MOSFET or the synchronous rectifying MOSFET is on. The input current is dominated by the current into the power stage, which averages about 70 mA (half of the peak current in the inductor).

Figure 3 shows an enlarged view of phase #1. Once the output voltage drops below the threshold, the TPS61220 begins a switching pulse by turning the control MOSFET on. The SW pin goes low, causing the inductor current to ramp up. It then turns off the control MOSFET and turns on the rectifying MOSFET, allowing current to flow to the output. The output voltage increases as this energy is transferred into the output capacitor. When the inductor current reaches zero, all the energy has been delivered to the output; so the rectifying MOSFET turns off, and the IC goes into a sleep mode (phase #2). At this point, both MOSFETs are off (open), so the SW pin is in a state of high impedance. The inductor and parasitic capacitances on that pin ring until it reaches its DC value, which equals the input voltage.

Figure 2. No-load operation of TPS61220

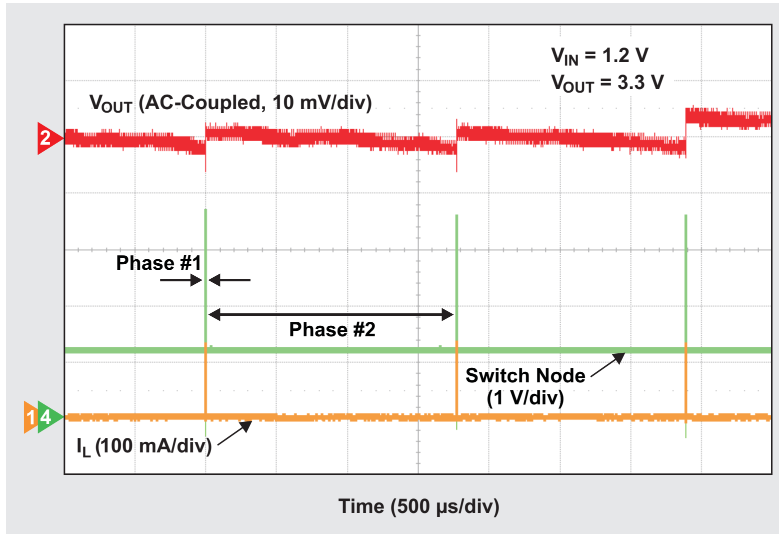
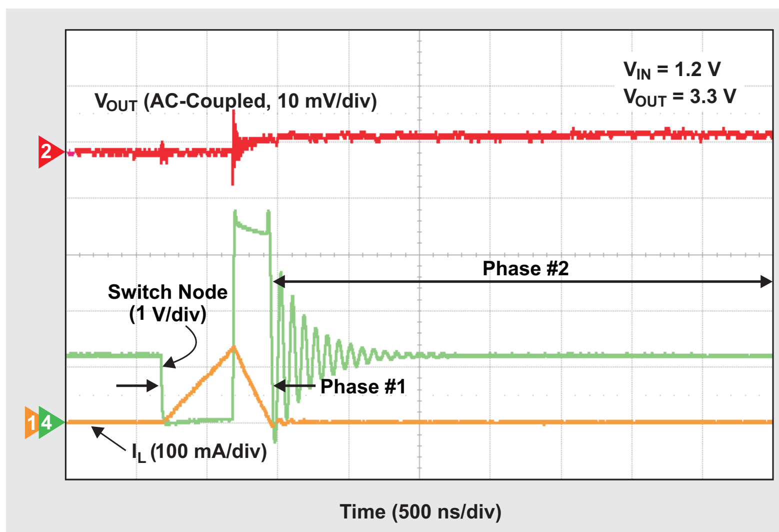


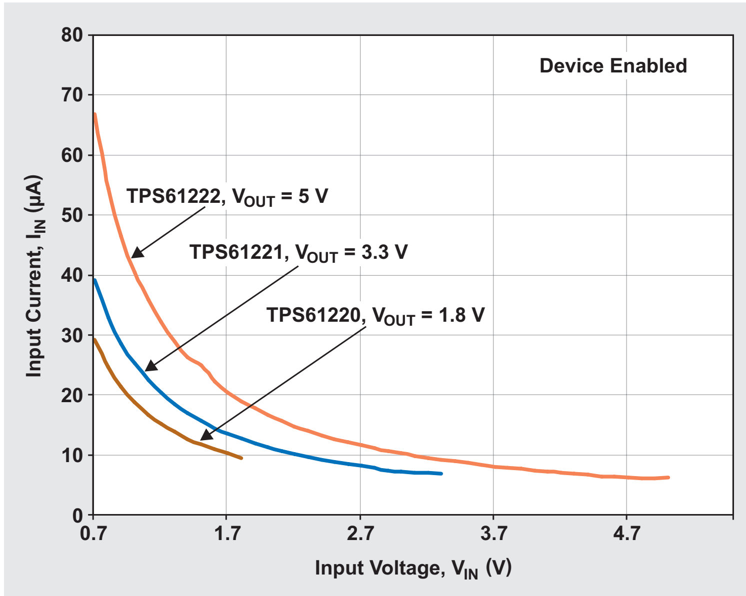
Figure 3. Switching pulse of TPS61220 during no-load operation



During phase #2, the IC is high impedance, and the output voltage drops due to leakage at the output. Because the IC is not switching, the current consumed by the IC during this time is the I_Q. Phases #1 and #2 define a switching period over which the average input current is calculated. Due to the high input current during the switching time (phase #1), the average input current over this time must be higher than the IC's I_Q. However, because the duration of phase #1 is very short, the average input current is usually only slightly greater than the input current that is due to the I_Q.

To address this difference between the I_Q and the no-load input current, the datasheets of some ICs have typical specifications for the no-load input current in the electrical characteristics table. Others have graphs that show the

Figure 4. Graph of no-load input current from TPS61220/21/22 datasheet



no-load input current for a particular circuit. Figure 4 shows such a graph from the TPS61220/21/22 datasheet.[1] Alternatively, Figure 5 shows the I_Q specification in an electrical characteristics table. This table is taken from the datasheet for the TI TPS62120/22,[2] which are high-efficiency buck converters. The typical specification of 13 µA is valid only for the specific test conditions stated. For both the TPS61220 and TPS62120, note that the no-load input current is higher than the IC's I_Q. Figure 4 shows that the no-load input current to the TPS61221 boost converter is 20 µA with a V_{IN} of 1.2 V and a V_{OUT} of 3.3 V. This is much higher than the I_Q in Figure 1 of 5 µA at V_{OUT} and 0.5 µA at V_{IN} with the same test conditions. This difference is explained later in this article under item #3 of "Design considerations."

How to use I_Q

Knowing the I_Q assists the designer in comparing the low-power performance of different ICs. However, an IC's I_Q is only part of the system's input current, which is affected by three things: each IC's internal design (its I_Q), the external components around each IC, and the overall system configuration. Because the input current is a combination of these three items, I_Q losses may or may not be the dominant loss for a particular system and may or may not be the determining factor in the battery's run time.

If the end application truly operates the IC at no output load, then an IC with lower I_Q typically has lower no-load input current, which results in longer battery run time. This assumes that both ICs have a power-save mode and that it is enabled. However, power-save modes can behave differently among different ICs, resulting in vastly different no-load input currents.

If the application does not run at no load but instead runs in a "standby" or "hibernate" mode in which the processor or another load still draws some current, then the usefulness of I_Q quickly decreases. To demonstrate, consider the TPS62120 powering TI's MSP430™ and other circuitry that altogether consume 100 µA at 2 V. With an 8-V input, the TPS62120 is running at 60% efficiency (see

Figure 5. No-load input-current specification from TPS62120/22 datasheet

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
SUPPLY						
I_Q	Quiescent current	I_{OUT} = 0mA, Device not switching, EN = VIN, regulator sleeps		11	18	µA
		I_{OUT} = 0mA, Device switching, V_{IN} = 8 V, V_{OUT} = 1.8V		13		µA

Figure 6. Efficiency graph for TPS62120

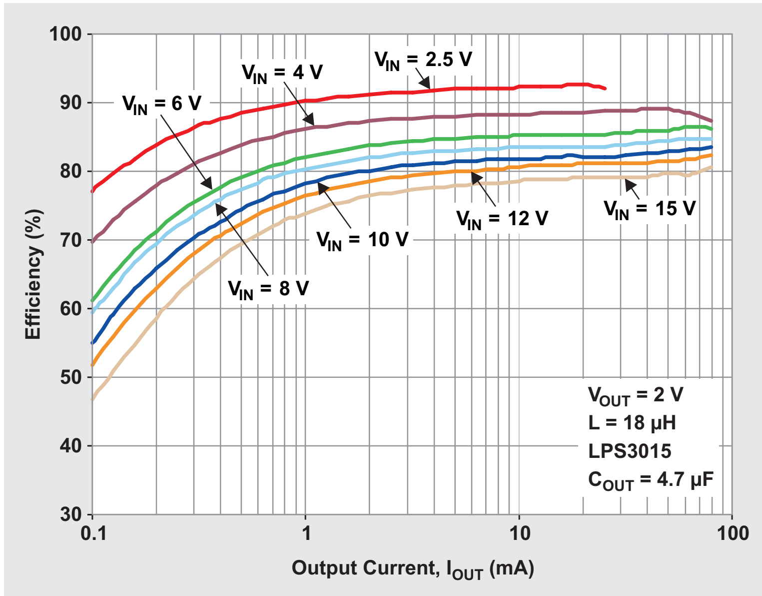


Figure 6[2]), resulting in an input current of

$$\frac{2\ \text{V} \times 100\ \mu\text{A}}{0.6 \times 8\ \text{V}} = 42\ \mu\text{A}.$$

This input current includes the I_Q (11 µA), which is a very significant portion of the total input current (about 26%). If, however, the standby load increases to 1 mA, the input current at 8 V is

$$\frac{2\ \text{V} \times 1\ \text{mA}}{0.8 \times 8\ \text{V}} = 313\ \mu\text{A}.$$

Now the 11 µA of I_Q is not significant at all (about 3.5%). To accurately estimate the input current in a system's standby mode, the load current drawn must be known. Simply using the I_Q in place of this light-load input current does not accurately estimate the battery current drawn.

Any efficiency graph in a datasheet indicates the total circuit efficiency and includes the I_Q losses. Therefore, the I_Q losses should not be added to the losses given in the graphs.

Design considerations

Numerous errors can be made when I_Q values are measured or taken from a datasheet. The following five considerations will help the designer avoid these errors.

1. **The I_Q of an IC cannot be changed.** Nothing can be done from outside the IC that affects the I_Q. The I_Q does vary over input voltage and temperature, but the behavior of the IC's internal circuitry sets this variation. If the IC is operated in forced PWM mode or a load is attached to the output, then the I_Q is no longer applicable to the circuit, and the input current becomes applicable instead. Many things can be done in an application that affect the input current, but not the I_Q.
2. **Specified operating conditions need to be considered.** I_Q is specified only for an IC's recommended operating conditions and for certain test conditions, specifically an input voltage and an output voltage. For any IC, the specified I_Q is not guaranteed when the input voltage is above the recommended maximum (but less than the absolute maximum) or when the input voltage is below the recommended minimum (but above the UVLO level). For a buck converter, I_Q is valid only when the input voltage is greater than the output voltage and when the device is not in dropout (100% mode). For a boost converter, the input voltage must be less than the output voltage so that the IC is not in down mode.
3. **Input current is often linked to the output.** The majority of the I_Q for a synchronous boost usually comes from the output voltage. Since this power must ultimately come from the input, the input current in a no-load condition is substantially higher than the I_Q because the input current for a boost converter must be greater than its output current. Consider the TPS61220 boosting from 1.2 V to 3.3 V. With an I_Q of 5 µA at V_{OUT} and 0.5 µA at V_{IN}, and assuming 100% conversion efficiency, the input current from the I_Q alone is

$$\frac{3.3\ \text{V} \times 5\ \mu\text{A}}{1.2\ \text{V}} + 0.5\ \mu\text{A} = 14.25\ \mu\text{A}.$$

The circuit actually draws about 20 µA of input current at no load (as shown in Figure 4) simply because of non-I_Q losses such as switching losses and gate-drive losses. The important point is that this 20 µA of input current is much greater than the IC's I_Q of 5.5 µA because the TPS61220 is a boost converter that draws most of its I_Q from the output voltage.

4. **Look for all possible input-current paths.** When measuring the I_Q on an evaluation module (EVM) or other board, the designer should ensure that the input current to the board is going entirely into the IC and not to other places on the board. Leakages from capacitors or other devices, even if the devices are disabled, may be significant due to the small I_Q values and may affect the input current to the board. In addition, on some EVMs and most end-equipment boards, the input voltage or output voltage is routed to pull-up resistors, indicator LEDs, or other devices that may sink current under some conditions. Obviously, this current draw is not part of the IC's I_Q. Finally, the IC's I_Q is of no importance as a system parameter, since total input current is actually what is needed; and that is easily measured at the required test conditions.
5. **Measurement techniques can make a big difference.** To get accurate measurements of the low-power input current or the efficiency in power-save mode, it is critical to follow the test setup detailed in Reference 3.

Conclusion

I_Q is an important IC design parameter in modern low-power DC/DC converters and partially defines the current drawn from the battery in light-load conditions. The I_Q is not the IC's no-load input current, as the IC consumes the I_Q current only in a no-load, enabled, and nonswitching condition. Due to leakage at the output, the IC must switch to keep the output voltage regulated. Instead of using an IC's I_Q as an estimate of the battery's current draw, the designer should measure and use the no-load input current to the system. An even better way to estimate the battery's current draw is to define the system's load when the system is in low-power mode and then measure the battery's actual current draw at this operating point. Doing this instead of simply using I_Q allows accurate prediction of battery run times.

References

For more information related to this article, you can download an Acrobat® Reader® file at www.ti.com/lit/*litnumber* and replace "*litnumber*" with the **TI Lit. #** for the materials listed below.

Document Title	**TI Lit. #**
1. "Low input voltage step-up converter in 6 pin SC-70 package," TPS61220/21/22 Datasheet	slvs776
2. "15V, 75mA high efficient buck converter," TPS62120/22 Datasheet	slvsad5
3. Jatan Naik, "Performing accurate PFM mode efficiency measurements," Application Report	slva236

Related Web sites

power.ti.com
www.ti.com/sc/device/TPS61220
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